International Journal of Civil Engineering and Technology (IJCIET)
Volume 8, Issue 3, March 2017, pp. 868–877 Article ID: IJCIET_08_03_087
Available online at http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=3
ISSN Print: 0976-6308 and ISSN Online: 0976-6316

STRUCTURAL BEHAVIOUR OF HOLLOW STEEL SECTIONS UNDER COMBINED AXIAL COMPRESSION AND BENDING

Amla Dash
P.G. Student, Department of Civil Engineering, SRM University,
Chennai, Tamil Nadu, India

D. Arul Prakash
Assistant Professor, Department of Civil Engineering, SRM University,
Chennai, Tamil Nadu, India

ABSTRACT

Hollow steel section has been used in variety of structural applications for its specific properties of durability and aesthetic appearance. The behaviour of hollow section under the effect of combined loading has been a significant research and therefore is the subject of the present study. This paper examines the behaviour of hot rolled hollow steel sections subjected to combined axial compression and bending. Numerical investigation has been carried out on various cross sections of rectangular hollow section (RHS), circular hollow section (CHS) and elliptical hollow section (EHS). In general, numerical analyses were performed including 12 pure axial compression loading, 24 uniaxial bending plus axial loading and 24 biaxial bending plus axial loading. Eccentricities for uniaxial and biaxial loading were varied to provide a wide range of possible values. Parametric studies have been done to predict section capacity of the cross sections to evaluate the codal provision given in Indian Standard 800:2007 and European code 1993-1-1-2005. The results from the numerical investigation on comparison with the predicted strength capacity of the cross sections from the codes represent consistency and have given good level of accuracy.

Key words: Combined loading, Numerical investigation, Parametric studies, Predicted section capacity.

Cite this Article: Amla Dash and D. Arul Prakash, Structural Behaviour of Hollow Steel Sections Under Combined Axial Compression and Bending. *International Journal of Civil Engineering and Technology*, 8(3), 2017, pp. 868–877.
http://www.iaeme.com/IJCIET/issues.asp?JType=IJCIET&VType=8&IType=3

1. INTRODUCTION

Hollow steel sections (HSS) are gaining a wide prospective in engineering applications due to its structural efficiency, aesthetic appearances, material properties and tubular profiles with concrete infilling to achieve higher load carrying capacities. HSS are metal sheet profile with a hollow tubular cross section manufactured in the form of hot rolled sections. These profiles are produced in the variety of rectangular hollow section (RHS), square hollow section (SHS), circular hollow section (CHS) and elliptical hollow section (EHS). According to EN 10210-1, structural steel sections are hot rolled above re-crystallisation temperature of the material [1], which results in good ductility, homogenous material property and low residual stress. In recent years, studies have been conducted to investigate the structural behaviour of hollow sections.

Ou Zhao, Leroy Gardner and Ben Young [2], have conducted experimental tests and numerical modeling on various CHS to obtain the section load carrying capacity and deformation under combined loading. In the companion paper [3], the results from experimental and numerical modeling were compared with the cross sectional capacities predicted from the EN 1993-1-4, SEI/ASCE-8 and AS/NZS 4673. The results obtained safe but scattered which can be overcome by continuous strength method design approach. Ou Zhao, Barbara Rossi, Leroy Gardner, Ben Young [4], have experimentally investigated the structural behaviour RHS and SHS under combined loading and have compared the results in the companion paper [5]. The comparison revealed that the codal design standards underestimate the cross section resistances capacity subjected to combined loading. L. Gardner, T. M. Chan and J. M. Abela [6], have conducted experimental and numerical simulation on EHS under combined compression and uniaxial bending. The result data were used to propose the interaction expression for the design of EHS.

Significant research has been carried out on the structural behaviour of hollow steel sections under combined loading and is the focus of the present study. This paper describes the numerical and parametric studies conducted on the hollow steel section of varying cross sectional dimensions subjected to combined loading. The numerical study includes finite element models of RHS, CHS and EHS respectively, subjected to various concentric and eccentric loads. The parametric study is carried out to predict the section capacity of the cross section using IS 800 2007 (General construction in steel – Code of Practice) [7] and EN 1993-1-1-2005 (Design of steel structures – General rules and rules for buildings) [8]. The load carrying capacity of the sections, obtained from the numerical investigations, is compared for the accuracy of the derived strength prediction from the codes.

2. NUMERICAL MODELLING

A wide range of cross sections of RHS, CHS and EHS were adopted for the numerical investigations and parametric studies, to understand the behaviour of the hollow sections when combined loadings are applied. For the numerical modelling, seven RHS, CHS and EHS respectively cross sections were employed. All the cross sections are having a aspect ratio of two, hot rolled carbon steel grade S355 and the sectional properties are according to EN 10210-2 [1], as presented in Table 1, 2, and 3. The numerical analysis comprised of 12 pure axial compression loading, 24 uniaxial bending plus axial loading and 24 biaxial bending plus axial loading. The slenderness limits are according to IS 800 2007 [7], for all sections. The adopted section specifies a model number (e.g. R4) consisting of a letter and a number, the letter represents the profile of the section as follows: (R) RHS, (C) CHS, (E) EHS and the number indicates the order of profile, this is to identify the section under the type of loading.

Table 1 Rectangular hollow section dimensions

Section dimension	Model ID	Height (mm)	Thickness (mm)	Area (mm^2)	Slenderness ratio
RHS 80x40x4	R1	1000	4	879	125.79
RHS 80x40x5	R2	1000	5	1070	129.03
RHS 100x50x4	R3	1200	4	1120	118.23
RHS 100x50x5	R4	1200	5	1370	120.60
RHS 120x60x5	R5	1500	5	1670	123.46
RHS 120x60x6.3	R6	1500	6.3	2070	126.58
RHS 160x80x6.3	R7	2000	6.3	2820	122.70

Table 2 Circular hollow section dimensions

Section dimension	Model ID	Height (mm)	Thickness (mm)	Area (mm^2)	Slenderness ratio
CHS 48.3x4	C1	1000	4	557	127.39
CHS 48.3x5	C2	1000	5	680	129.87
CHS 60.3x4	C3	1200	4	707	120.00
CHS 60.3x5	C4	1200	5	869	122.45
CHS 88.9x4	C5	1800	4	1070	120.00
CHS 88.9x5	C6	1800	5	1320	121.21
CHS 88.9x6.3	C7	1800	6.3	1630	122.87

Table 3 Elliptical hollow section dimensions

Section dimension	Model ID	Height (mm)	Thickness (mm)	Area (mm^2)	Slenderness ratio
EHS 120x60x3.2	E1	1300	3.2	870	119.27
EHS 120x60x4	E2	1300	4	1080	120.93
EHS 120x60x5	E3	1300	5	1340	122.64
EHS 150x75x4	E4	1700	4	1360	125.00
EHS 150x75x5	E5	1700	5	1690	126.39
EHS 150x75x6	E6	1700	6	2010	128.30
EHS 180x90x6	E7	2000	6	2430	124.22

2.1. Basic Modelling

A numerical modelling programme was carried out using the finite element package ANSYS, to investigate the section capacity and load-deflection curves, followed by the parametric studies to produced strength prediction data of the cross sections. A four noded shell element with six degrees of freedom at each node was used as the element type in the numerical modelling. The shell element is suitable for analysing thin or thick shell structures. A uniform mesh of cross section thickness was assigned to each modelled section to generate a finer mesh to increase the accuracy of results as shown in Figure 1.

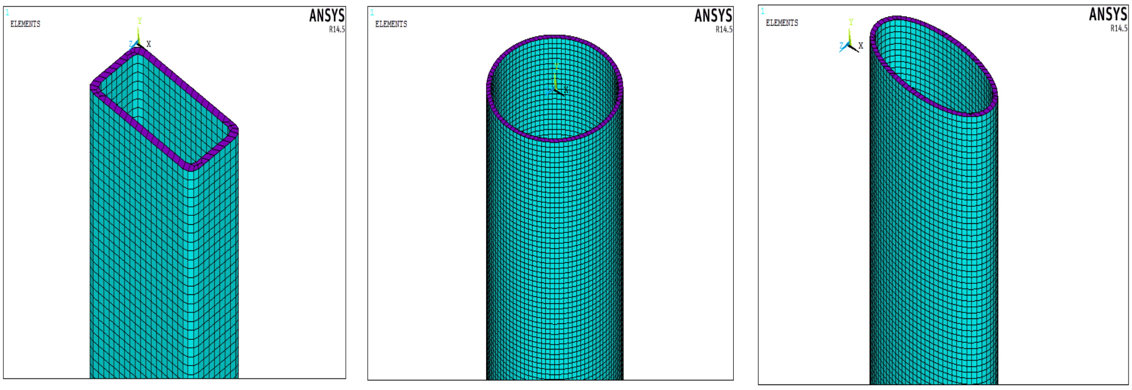


Figure 1 Meshed model of sections

The sections were modelled to their true cross section and length. The material properties required for the analysis were in the format of bilinear stress strain curve The linear elastic material property was applied to the models as the Young's modulus (E=210000 N/mm^2) and Poisson's ratio (μ=0.3). A nonlinear finite element analysis was conducted to determine the section capacity of the section.

The boundary condition applied at one end was fixed end condition while allowing translation and rotation about the loaded end of the section. The eccentricities applied were varied to cover a wide range of possible values. For pure axial compression, the load (N) was applied at concentric reference point. For combined loading, the nodes of the loaded end were coupled to the eccentric reference point through constrain equation.

Table 4, 5 and 6 reports the results obtained from numerical investigations. The load–deflection curves of axial compression loading are shown in Figure 2-4, uniaxial bending plus axial loading are shown in Figure 6 and biaxial bending plus axial loading are shown in Figure 7. Figure 5 represents the von Mises stress distribution of the section.

Table 4 Axial compression results summary

Section dimension	Model No.	Ultimate Load Nu (kN)	Displacement (mm)
RHS 80 x 40 x 4	R1	610	1.70
RHS 100 x 50 x 5	R4	953	2.04
RHS 120 x 60 x 6.3	R6	1432	2.55
RHS 160 x 80 x 6.3	R7	1970	3.43
CHS 48.3 x 5	C2	1020	1.70
CHS 60.3 x 4	C3	1030	2.00
CHS 88.9 x 4	C5	1500	2.94
CHS 88.9 x 5	C6	1910	3.01
EHS 120 x 60 x 4	E2	795	2.19
EHS 120 x 60 x 5	E3	1000	2.86
EHS 150 x 75 x 4	E4	984	2.19
EHS 180 x 90 x 6	E7	1790	3.38

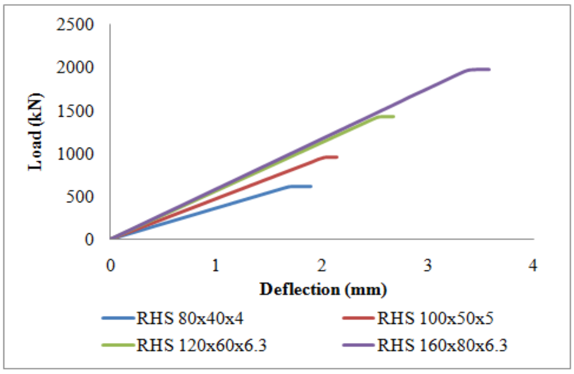


Figure 2 Load-Deflection curve of RHS under axial loading

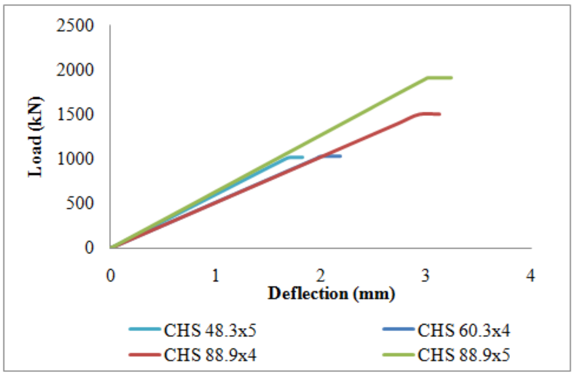


Figure 3 Load-Deflection curve of CHS under axial loading

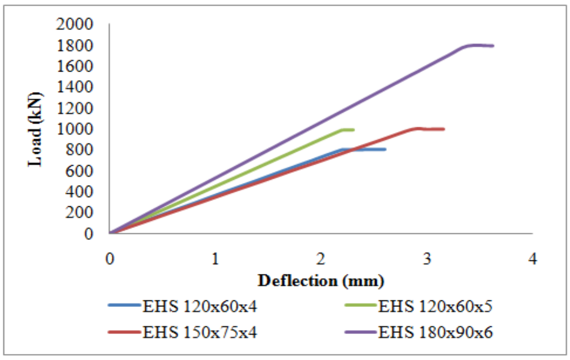


Figure 4 Load-Deflection curve of EHS under axial loading

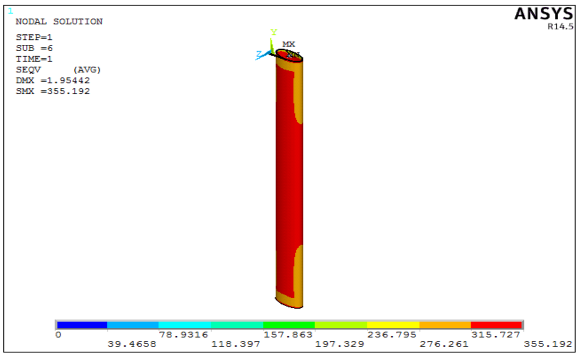
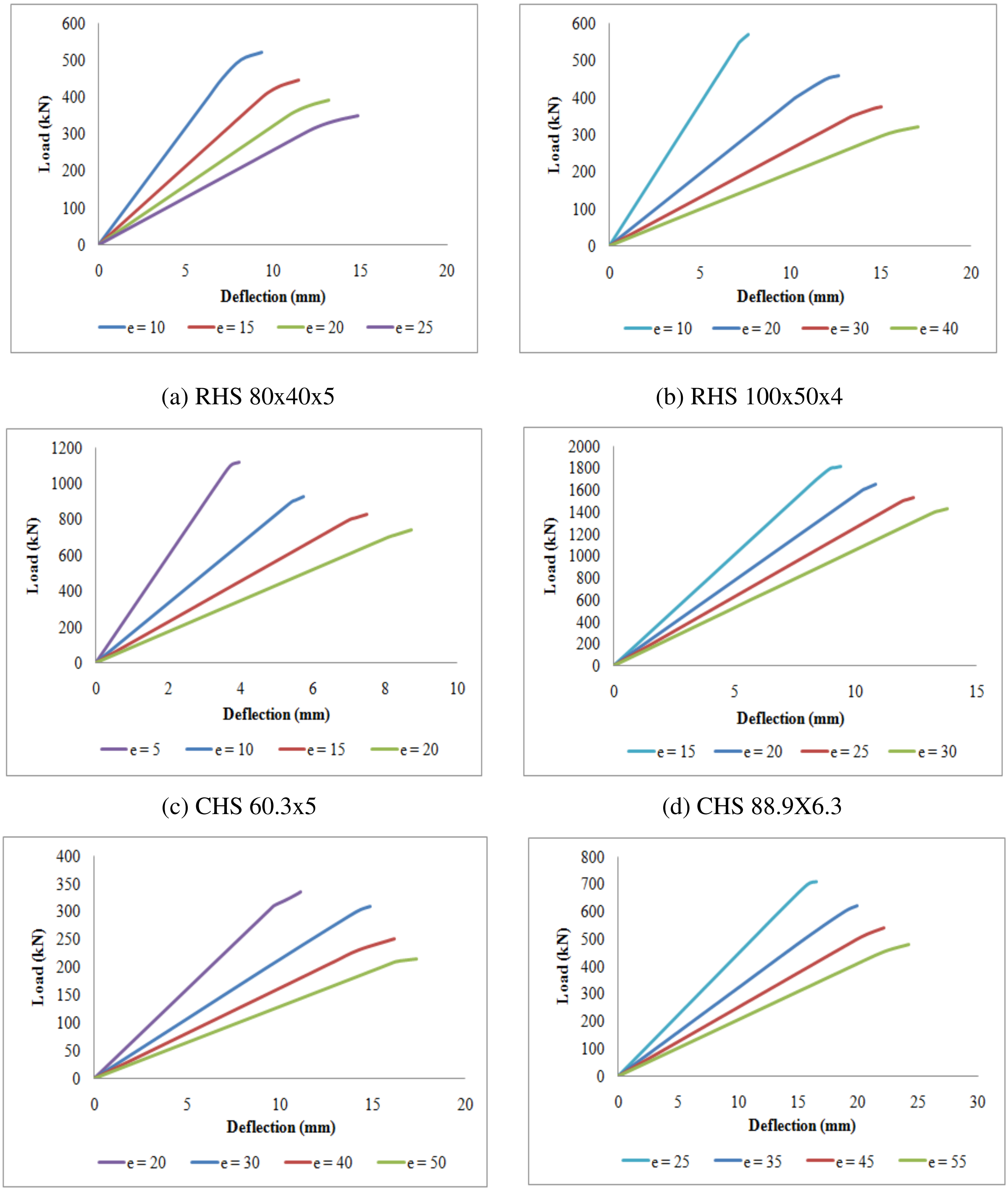


Figure 5 von Mises stress distribution of elliptical cross sections.

Table 5 Uniaxial bending plus axial load results summary

Section dimension	Model No.	Eccentricity (mm)	Axial Load Nu (kN)	Uniaxial Moment Mu (kN-m)
RHS 80x40x5	R2	10	500	5.0
		15	420	6.3
		20	370	7.4
		25	340	8.5
RHS 100x50x4	R3	10	550	5.5
		20	450	9.0
		30	370	11.1
		40	310	12.4
CHS 60.3x5	C4	5	1100	5.5
		10	910	9.1
		15	810	12.15
		20	720	14.4
CHS 88.9x6.3	C7	15	1800	27.0
		20	1610	32.2
		25	1510	37.75
		30	1410	42.3
EHS 120x60x3.2	E1	20	335	6.7
		30	320	9.6
		40	250	10.0
		50	215	10.75
EHS 150x75x5	E5	25	700	17.5
		35	600	21.0
		45	520	23.4
		55	480	26.4



(a) RHS 80x40x5

(b) RHS 100x50x4

(c) CHS 60.3x5

(d) CHS 88.9X6.3

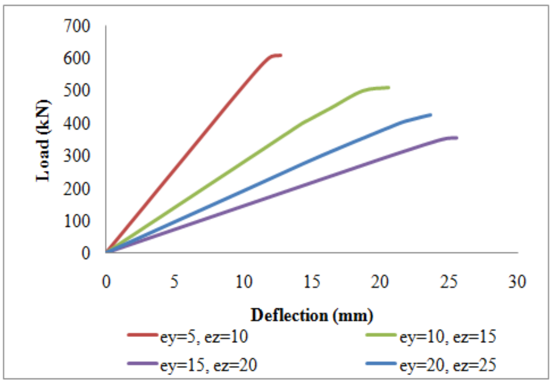
(e) EHS 120x60x3.2

(f) EHS 150x75x5

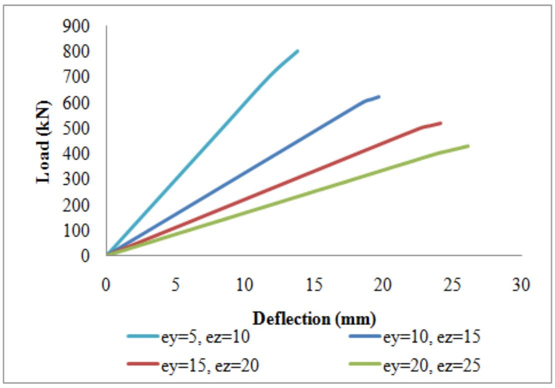
Figure 6 Load–deflection curves for uniaxial bending plus axial loading

Table 6 Biaxial bending plus axial load results summary

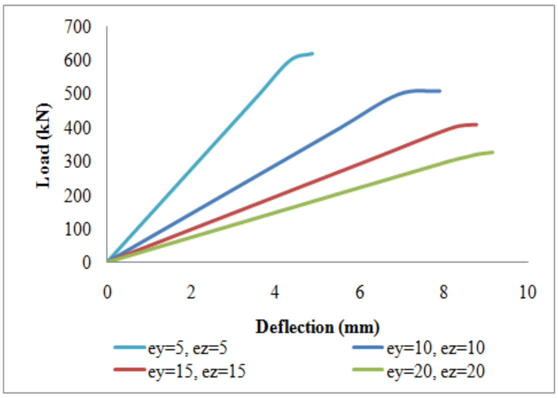
Section dimension	Model No.	Eccentricity @ major axis (mm)	Eccentricity @ minor axis (mm)	Axial Load Nu (kN)	Moment @ major axis (kN-m)	Moment @ minor axis (kN-m)
RHS 100x50x5	R4	5	10	600	6.0	3.0
		10	15	500	7.5	5.0
		15	20	410	8.2	6.15
		20	25	350	8.75	7.0
RHS 120x60x5	R5	5	10	800	8.0	4.0
		10	15	610	9.15	6.1
		15	20	510	10.2	7.65
		20	25	430	10.75	8.6
CHS 48.3x4	C1	5	5	600	3.0	3.0
		10	10	500	5.0	5.0
		15	15	400	6.0	6.0
		20	20	320	6.4	6.4
CHS 60.3x5	C4	10	15	800	12.0	8.0
		15	20	700	14.0	10.5
		20	25	620	15.5	12.4
		25	30	550	16.5	13.75
EHS 120x60x5	E3	5	10	660	6.6	3.3
		10	20	500	10.0	5.0
		15	30	420	12.6	6.3
		20	40	340	13.6	6.8
EHS 150x75x6	E6	5	10	1060	10.6	5.3
		10	20	820	16.4	8.2
		15	30	700	21.0	10.5
		20	40	600	24.0	12.0



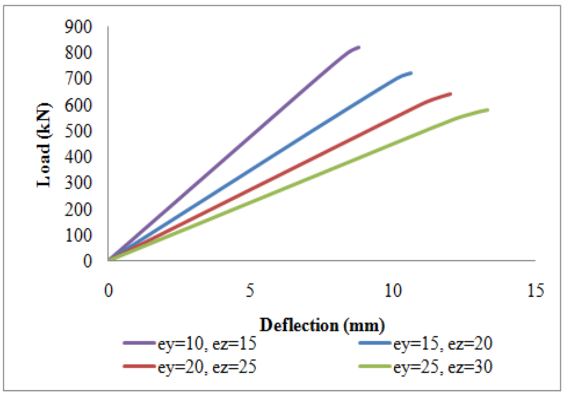
(a) RHS 100x50x5



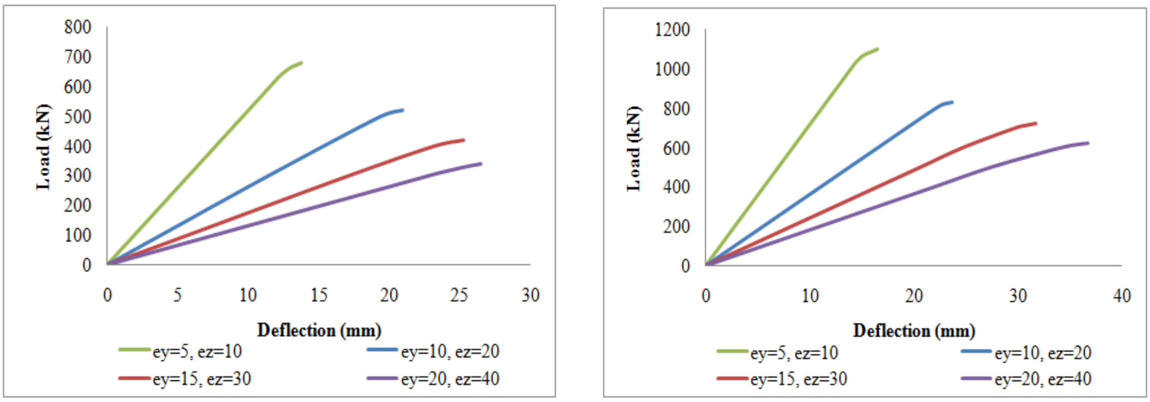
(b) RHS 120x60x5



(c) CHS 48.3x4



(d) CHS 60.3x5



(e) EHS 120x60x5 (f) EHS 150x75x6

Figure 7 Load–deflection curves for biaxial bending plus axial loading

3. PARAMETRIC STUDY

The parametric studies were conducted for hollow steel sections under combined loading. The cross sectional resistance were predicted by the methods given in IS 800 2007 [7] and EN 1993-1-1-2005 [8]. The cross sectional strength predicted from the codal provision is evaluated through comparing the ratios of the results obtained by numerical investigation to predicted section capacities. Figure 8 represents the interaction curve of axial load and moment [3] defining that the theoretical predicted capacity ($N_{u,pred}$) lies on the interaction curve and the FE section capacity (N_u), lies outsides the curve which is considered safe. The strength predicted by the code is factored design strength.

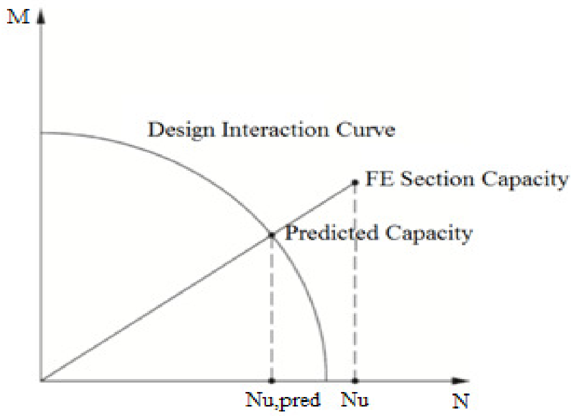


Figure 8 Interaction curve of load and moment

3.1. Indian Standard IS 800 2007

The current Indian Standard IS 800 2007 [7] has given a conservative interaction equation to predict section strength under combined loading, as given by equation (1). The equation (1) states a linear summation of ratios of applied load (N) and moment (M) to predicted design strength under axial load (N_d) and bending moment (M_d). N is the axial load applied. The applied moment M is equal to the product of axial load (N) and corresponding eccentricity (e). N_d is the design axial strength due to yielding, is given as, the product of gross area (A_g) and yield stress (f_y) of the material. M_d is the codal design strength equal to the product of plastic section modulus (Z_p) of the cross section and yield stress (f_y).

$$\frac{N}{Nd} + \frac{My}{Mdy} + \frac{Mz}{Mdz} \leq 1.0 \quad (1)$$

3.2. European Code 1993-1-1-2005

The Eurocode for design of steel structures 1993-1-1-2005 [8] has given the same interactive equation to predict the cross sectional resistance. The equation (2) states the design expression, in which N_{Ed} is the design normal force. M_{Ed} is the design bending moment is equal to the product of normal force (N_{Ed}) and corresponding eccentricity (e). N_{RD} is equal to the product of cross sectional area (A) and yield stress (f_y). M_{RD} is equal to the product of plastic section modulus (W_{pl}) and yield stress (f_y).

$$\frac{N_{ED}}{N_{,RD}} + \frac{My_{,ED}}{My_{,RD}} + \frac{Mz_{,ED}}{Mz_{,RD}} \leq 1.0 \quad (2)$$

Table 7 and 8 reports the $N_u/N_{u,pred}$ ratios for combined loading, where N_u is the FE result and $N_{u,pred}$ is the predicted section capacity of the cross section by the codes.

Table 7 Comparison of FE results with predicted strength for uniaxial bending plus axial loading

Sections	$Nu/Nu_{,IS800}$	$Nu/Nu_{,EC3}$
RHS 80 x 40 x 5	1.18	1.07
RHS 100 x 50 x 4	1.16	1.06
CHS 60.3 x 5	3.16	2.87
CHS 88.9 x 6.3	3.01	2.73
EHS 120 x 60 x 3.2	1.0	0.91
EHS 150 x 75 x 5	1.05	0.96

Table 8 Comparison of FE results with predicted strength for biaxial bending plus axial loading

Sections	$Nu/Nu_{,IS800}$	$Nu/Nu_{,EC3}$
RHS 100 x 50 x 5	1.05	0.96
RHS 120 x 60 x 5	1.09	0.99
CHS 48.3 x 4	2.53	2.3
CHS 60.3 x 5	2.38	2.16
EHS 120 x 60 x 5	1.11	1.01
EHS 150 x 75 x 6	1.23	1.11

4. CONCLUSION

A non linear finite element analyses were conducted on RHS, CHS and EHS models respectively under a set of combined loading. The FE models were capable of investigating the section capacities and load-deflection curves. The results obtained are based corresponding to the von Mises yield criterion. From the obtained results it is observed that the load carrying capacity of the section decreases as the eccentricity of the load increases. The ultimate load carrying capacity of the section is achieved when the model becomes unstable at a point due to large deflection.

The ratio of FE result to the predicted design strength (Nu/Nu,pred) of the section is obtained using various codes. The strength predicted using Indian Standard 800 [7] is found out to be greater than unity for all analysed sections and is considered safe. The strength predicted using Eurocode 3 [8] is found out to be greater than unity except for EHS 120x60x3.2 and EHS 150x75x5 under uniaxial loading and RHS 100x50x5 and RHS

120x60x5 under biaxial loading. The ratios of the above sections are marginally less than unity, hence they are considered to be predicted safely.

On comparing the ratios, Indian Standard 800 [7] has safely predicted design strength than Eurocode 3 [8] because of the factor of safety adopted. The result also represents that the strength predicted from the codal provision neglect the effect of strain hardening in the model. This can be improved by adopting continues strength methods which incorporate strain hardening effects.

The ratios also shows that the load carrying capacity determined by the numerical investigation of RHS and EHS models respectively appears to be closer, to the predicted design strength of the section from the codes whereas the result obtained for the CHS models appears to be more than the predicted design strength. Therefore, CHS cross sections have better load carrying capacity according to the numerical analysis. Overall, on comparison the results predicted are safe.

REFERENCES

[1] EN 10210, Hot-finished structural hollow sections of non-alloy and fine grain steels, European Standard, CEN, 2006.

[2] Ou Zhao, Leroy Gardner and Ben Young, Structural performance of stainless steel circular hollow sections under combined axial load and bending – part 1: experiments and numerical modelling, Thin Walled Structures 101, 2016, 231-239.

[3] Ou Zhao, Leroy Gardner and Ben Young, Structural performance of stainless steel circular hollow sections under combined axial load and bending – part 2: parametric studies and design, Thin Walled Structures 101, 2016, 240-248.

[4] Ou Zhao, Barbara Rossi, Leroy Gardner and Ben Young, Behaviour of structural stainless steel cross-sections combined loading – part I: experimental study, Engineering structures 89, 2015, 236-246.

[5] Ou Zhao, Barbara Rossi, Leroy Gardner and Ben Young, Behaviour of structural stainless steel cross-sections combined loading – part II: numerical modeling and design approach, Engineering structures 89, 2015, 247-259.

[6] L. Gardner, T. M. Chan and J. M. Abela, Structural behaviour of elliptical hollow sections under combined load and uniaxial bending, Advanced steel construction Vol. 7, No. 1, 2011, 86-112.

[7] IS 800, Indian Standard: General construction in steel – Code of Practice, BIS 2007.

[8] EN 1993-1-1. Eurocode 3: Design of steel structures – part 1-1:general rules and rules for building, European Standard, CEN, 2005.